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WIND DRIFT OF SEA ICE: A SUPPLEMENT TO THE NAVAL OCEANOGRAPHIC --ETC(U)

SEP 76 D J GERSON, L S SIMPSON

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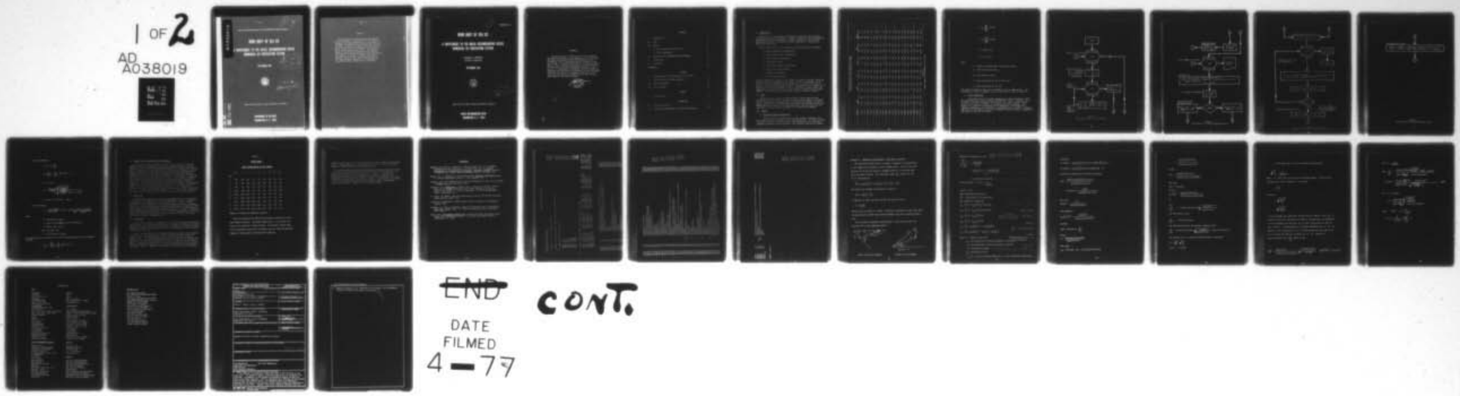

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NAVAL OCEANOGRAPHIC OFFICE REFERENCE PUBLICATION 8 - S

WIND DRIFT OF SEA ICE

A SUPPLEMENT TO THE NAVAL OCEANOGRAPHIC OFFICE NUMERICAL ICE FORECASTING SYSTEM

See 1473 in back

SEPTEMBER 1976

Approved for public release; distribution unlimited

DEPARTMENT OF THE NAVY
WASHINGTON, D. C. 20373

ABSTRACT

The numerical ice prediction system described in RP 8 has been in use since 1971. Its outputs, however, have been related only to ice growth, not ice drift. An addition to the system now provides an output of daily ice drift at 62 arctic stations. Drift is calculated as a function of wind stress, water stress, and Coriolis force. The computer output is sufficiently accurate for ice drift in the locality of the station whose wind observations were input to the model. However, more recent research indicates that for greater accuracy and for computations of divergence and convergence interaction between floes must be considered.

1

NOO RP 8 - S

WIND DRIFT OF SEA ICE

A SUPPLEMENT TO THE NAVAL OCEANOGRAPHIC OFFICE NUMERICAL ICE FORECASTING SYSTEM

DONALD J. GERSON

LLOYD S. SIMPSON

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FOREWORD

Fleet operations in the Arctic are often hindered, and sometimes aborted, by the severity of ice conditions. The Naval Oceanographic Office has pioneered in the development of ice forecasting support designed to permit the Navy to operate effectively at all times in arctic waters. This publication describes an automated program for computing ice drift for selected locations in the Arctic. It supplements a previously existing program for computing and predicting ice thickness for these locations. Ice drift, as well as ice thickness, information is required for mine warfare, submarine surfacings, surface ship transits, and sonobuoy plants.

J. E. AYRES
Captain, USN
Commander

A

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I. INTRODUCTION

Since July 1971 a numerical ice prediction system has been operated by the Naval Oceanographic Office to compute various sea ice characteristics and forecasting aids of importance to arctic operations. Gerson (1975) completely describes the system as of 1975; therefore, it will only be briefly discussed here.

The original outputs of the prediction system include the following:

* present degree-day accumulations
* forecast degree-day accumulations
* daily synoptic temperatures
* temperature trends
* selected sea surface temperatures
* initial freezeup forecasts
* reported snow depths
* ice thickness forecasts

All this information relates to ice formation, growth, thickness, and decay in-situ without consideration of ice drift. Since the knowledge of ice drift is extremely important to the forecaster, its inclusion as part of the daily output was considered desirable. The purpose of this report is to describe this significant update to the ice prediction system, namely the computation of wind drift of ice at each of the 62 stations in the present network. An example of a typical output listing is shown in figure 1.

II. DATA

The data are the same as used for the basic system, and are fully described in Gerson (1975). A slight revision in the heading is discussed in U. S. Department of Commerce (1973). The data base remains the entire world's synoptic weather observations collected by the National Oceanic and Atmospheric Administration, but observations for each day now are on one tape rather than two and are processed on its IBM 360/195 computer.

III. METHOD

A. Mean Wind Speed and Direction

The wind drift is derived entirely from values of synoptic wind speed and direction as reported by the network stations. The four (or fewer if reports are missing) daily synoptic wind observations are vectorially averaged to produce a mean wind speed. The equations used are as follows:

WIND SPEED (KTS) AND DIRECTION (DEG)
AND WIND DRIFT OF ICE FOR SEP 8, 1976

STATION	00Z		06Z		12Z		18Z		MEAN		DRIFT	
NO	SPD	DIR	SPD	DIR	SPD	DIR	SPD	DIR	SPD	DIR	SPD	DIR
21504	8.0	200	12.0	140	8.0	110	.0	360	5.8	148	.21	171
21647	16.0	90	14.0	110	18.0	140	18.0	140	15.9	122	.58	142
21824	12.0	160	12.0	160	4.0	270	4.0	200	6.6	175	.24	197
21965	16.0	70	12.0	50	10.0	50	12.0	50	12.3	56	.45	78
21982	14.0	340	20.0	360	10.0	290	22.0	340	15.3	340	.56	0
25173	12.0	320	16.0	320	14.0	290	20.0	320	15.1	314	.56	334
25399	14.0	200	4.0	200	12.0	360	18.0	360	3.6	336	.13	2
25594	10.0	200	10.0	20	14.0	50	.0	360	3.5	50	.13	76
70026	10.0	160	10.0	90	8.0	70	10.0	60	7.4	94	.27	116
70086	10.0	80	10.0	130	7.0	110	12.0	90	9.2	102	.34	123
70133	4.0	90	99.0	990	17.0	360	16.0	320	10.0	349	.27	10
70200	7.0	320	9.0	300	6.0	350	8.0	10	6.6	334	.24	356
70218	99.0	990	99.0	990	99.0	990	99.0	990	99.0	990	9.90	990
70273	11.0	300	6.0	130	6.0	90	4.0	360	1.4	11	.05	47
70308	20.0	330	99.0	990	20.0	290	99.0	990	18.8	311	.70	330
70316	21.0	340	22.0	310	18.0	310	99.0	990	19.7	321	.74	340
70326	4.0	280	.0	360	3.0	280	4.0	250	2.7	269	.10	297
70350	10.0	120	14.0	40	9.0	330	9.0	290	4.3	16	.16	40
72815	7.0	280	12.0	210	12.0	220	5.0	330	6.8	239	.26	261
72816	12.0	360	13.0	340	11.0	320	10.0	310	10.9	335	.41	355

Figure 1.
Sample output of wind velocity and ice drift

$$I = \frac{1}{k} \sum_{i=1}^{k} V_i \sin D_i \quad ,$$

$$J = \frac{1}{k} \sum_{i=1}^{k} V_i \cos D_i \quad ,$$

$$\bar{D} = \arctan (I/J) \quad ,$$

$$\bar{V} = (I^2 + J^2)^{\frac{1}{2}} \quad ;$$

where

k = number of observations (1-4) during the day,

D_i = wind direction at time i,

V_i = wind speed at time i,

$\bar{D}$ = mean wind direction for the day, and

$\bar{V}$ = mean wind speed for the day.

The computer program accounts for the quadrant in these computations. This subroutine is listed in appendix A, and a flow chart is shown in figure 2.

B. Drift Computation

The method used for ice drift computation is that of Shuleikin (1953). This method has been used by Wittmann and MacDowell (1964) to produce a set of curves for manual computation of ice drift. In order to obtain a daily output for 62 stations, however, an automated method is necessary. The equations as presented by Shuleikin do not immediately lend themselves to computer programming, and considerable transformation was required. A complete derivation of the equations used in the computer program is given in appendix B. The equations used are as follows:

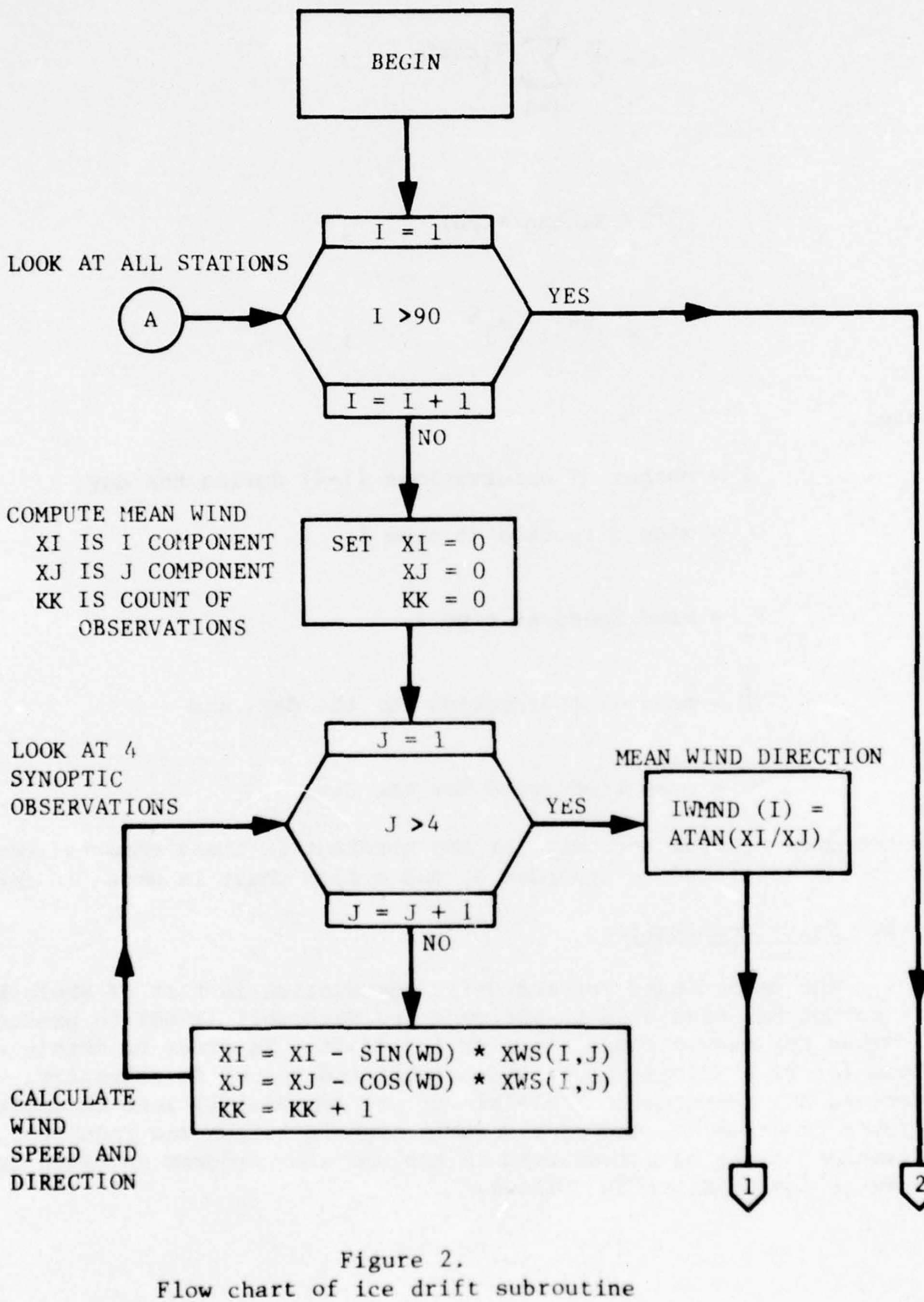

Figure 2.
Flow chart of ice drift subroutine

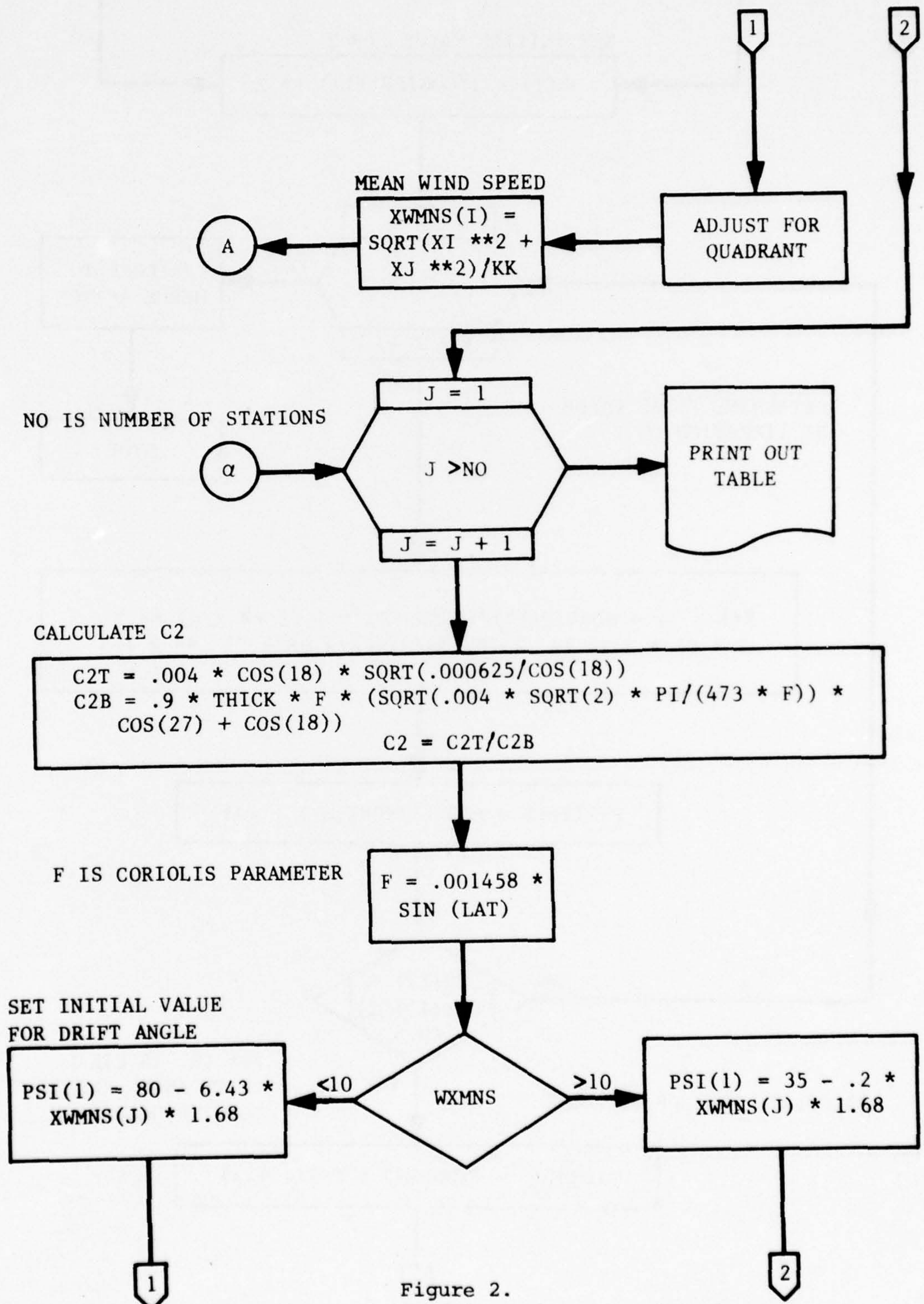

Figure 2.
Flow chart of ice drift subroutine (con.)

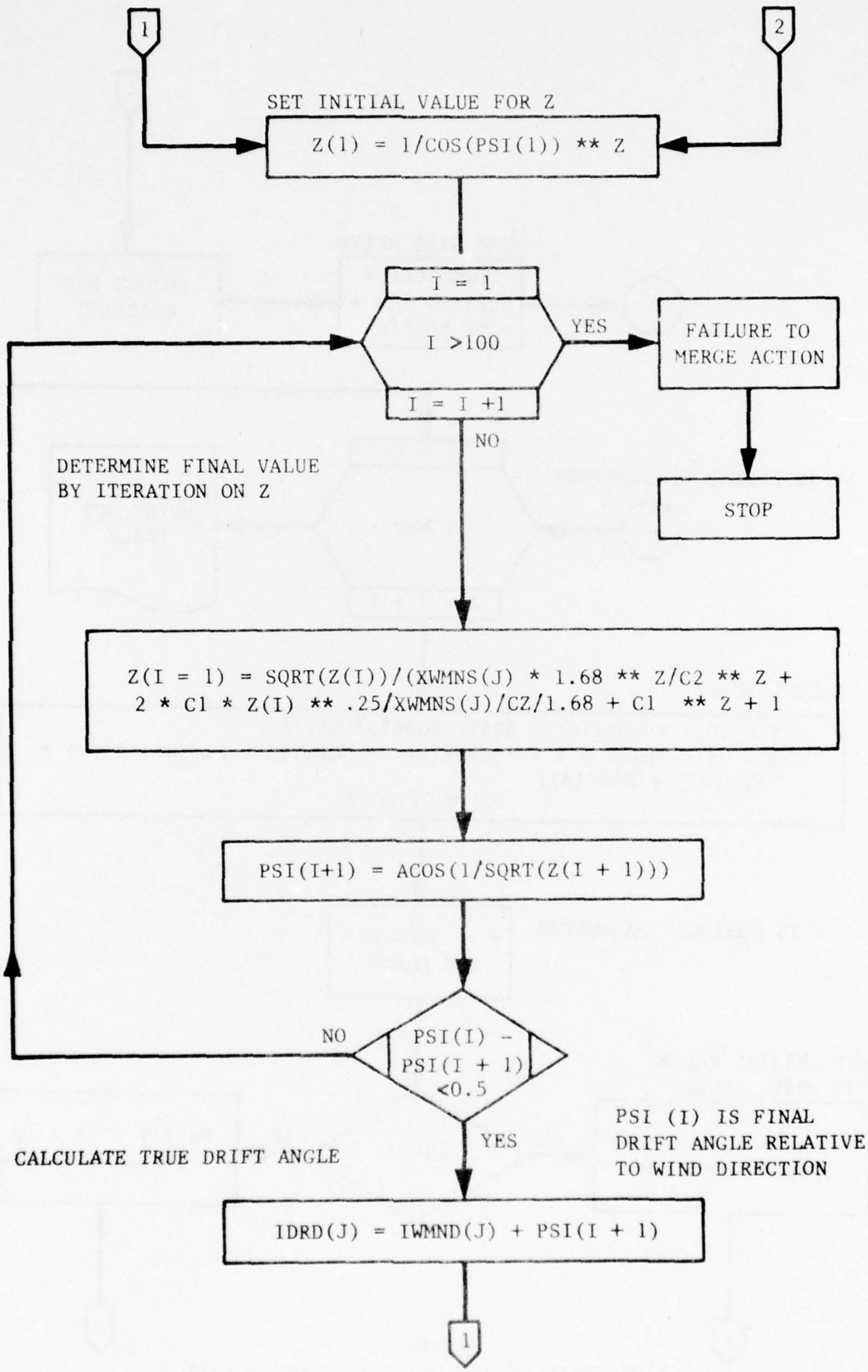

Figure 2.
Flow chart of ice drift subroutine (con.)

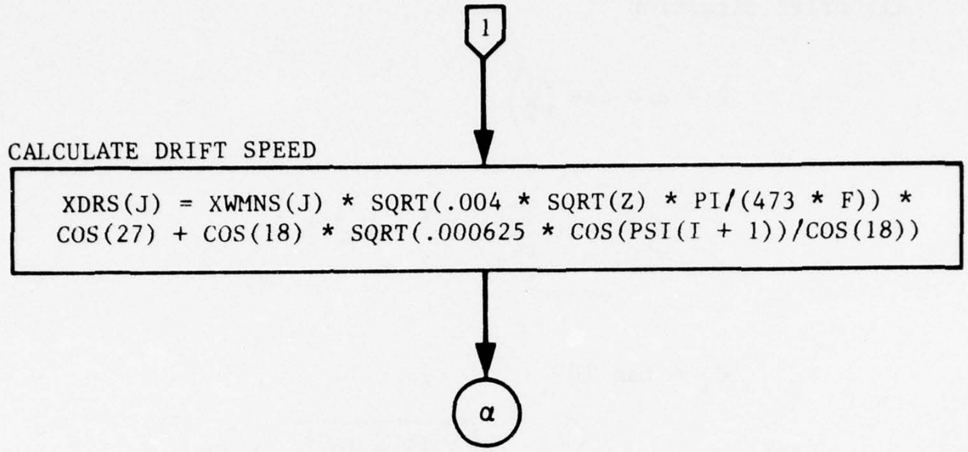

Figure 2.
Flow chart of ice drift subroutine (con.)

(1) drift direction

$$\psi = \text{arc cos}\left(\frac{1}{Z}\right) \quad ,$$

$$Z = \frac{Z^{\frac{1}{2}}}{V^2 C_2^{\,2}} + \frac{2C_1}{VC_2} \quad Z^{\frac{1}{4}} + C_1^{\,2} + 1 \quad ,$$

$$C_1 = \tan 18^\circ \quad ,$$

$$C_2 = \frac{.004\cos 18^\circ \sqrt{\dfrac{6.25 \times 10^{-4}}{\cos 18^\circ}}}{0.9fI\left[\sqrt{\dfrac{.004\sqrt{2\pi}}{473f}}\cos 27^\circ + \cos 18^\circ\right]} \quad ,$$

$$f = 1.458 \times 10^{-4}\sin(\text{lat}) \quad ; \text{ and}$$

(2) drift speed

$$u = V\left[\sqrt{\frac{.004\sqrt{2\pi}}{473f}}\cos 27^\circ + \cos 18^\circ\right]\sqrt{\frac{6.25 \times 10^{-4}\cos\psi}{\cos 18^\circ}} \quad ;$$

where

V = wind speed (ft/sec),

ψ = drift to the right of the wind direction

u = drift speed (ft/sec)

lat = latitude, and

I = ice thickness (inches)

The equation for Z is required to be in an iterative form, thus it is used as follows:

$$Z_{n+1} = \frac{Z_n^{\frac{1}{2}}}{V^2 C_2^{\,2}} + \frac{2C_1}{VC_2} \quad Z_n^{\frac{1}{4}} + C_1^{\,2} + 1$$

IV. VARIATION FOR CONCENTRATION AND ROUGHNESS

The Shuleikin equations assume a single ice floe and do not consider surface roughness. An empirical table of wind factors (Zubov, 1945) was compiled by P.A. Gordienko from many observations of ice drift in the Soviet Arctic. Comparison of this table with the output of the Shuleikin equations shows a match at 0.5 oktas and 4 tenths extent of ridging and hummocking. A factor table (table 1) was then constructed for use in correcting the computer output to the applicable concentration and roughness. Instructions for using the table are given beneath the table. As an example, suppose we have a mean wind speed and direction of 9.2 kn and 102 deg, which produce an ice drift and direction of .34 kn and 123 deg (see station 70086 in figure 1). If the concentration were 0.5 oktas and the extent of ridging and hummocking 4 tenths, then, referring to table 1, the ice drift speed would remain .34 kn since the multiplicative factor is 1. If, however, the concentration was 6 oktas and the ridging 3 tenths, the ice drift speed would be .10 kn since the multiplicative factor is .3. In either case, the drift direction remains 123 deg, since this table only relates to drift speed.

V. CONCLUSIONS

The methods described above have been programmed and are now operational on the UNIVAC 1108 computer at the Naval Oceanographic Office. Ice drift information is now regularly produced, together with the other products described in the Introduction. The outputs have been evaluated by comparing them first with the manual computation method of Wittmann and MacDowell (1964) and second with manual calculations accomplished with the original equations. These comparisons have proved the computer program to be reliable. Evaluation with actual observed drift conditions has not been accomplished, but since the curves from Wittmann and MacDowell have been used successfully for years, the computer output is assumed accurate.

VI. DISCUSSION

As previously stated, this computation of ice drift is based on Shuleikin's work of 1953. This model was chosen since it had been used manually for years and had been found to give accurate results. In addition, it was most easily adapted to estimating wind drift from station observations that were available in the existing system.

A basic problem exists with the Shuleikin model in that it only considers the motion of a single floe as it results from wind and water stress and Coriolis force. No consideration is given to the effect of interaction between floes. In the program herein described, the effects of concentration and ridging are considered empirically but are not input to the theoretical model. Considerable research has been done since Shuleikin's work. Many of the recent papers are published in the extensive AIDJEX series (University of Washington, 1972-). Campbell and Rasmussen (1972) begin with an excellent

Table 1

FACTOR TABLE

TOTAL CONCENTRATION OF ICE (OKTAS)

E*	0.5	1	2	3	4	5	6	7.0	7.5
1	.26	.24	.20	.17	.13	.10	.09	.07	.07
2	.51	.47	.40	.34	.28	.22	.18	.15	.12
3	.75	.71	.63	.55	.47	.39	.30	.22	.19
4	1.00	.96	.84	.72	.62	.51	.39	.29	.24
5	1.26	1.19	1.06	.92	.79	.65	.52	.38	.31
6	1.51	1.43	1.26	1.10	.94	.80	.63	.46	.38
7	1.75	1.66	1.47	1.29	1.10	.92	.73	.55	.46
8	2.01	1.90	1.69	1.49	1.28	1.07	.85	.64	.53
9	2.26	2.13	1.90	1.64	1.40	1.17	.94	.71	.60

*Extent of ridging and hummocking (tenths)

Table of multiplicative factors for estimating speed of ice drift from computer printout. The drift speeds given in the printout are true for 0.5 oktas and 4 tenths ridging. To determine correct speed enter concentration and extent of ridging into this table and multiply computer's drift speed by the factor thus obtained.

summary of ice dynamics up to 1972 and proceed to give a model that considers ice as a viscous material. Rothrock (1975) considers sea ice as a plastic material. Additional papers are expected shortly.

Ice drift estimates, computed by the model discussed in sections III and IV of this paper, are sufficiently accurate for use in the locality of the station whose wind reports are used in the calculation. They are not sufficiently accurate for the calculation of areas of convergence and divergence or for interpolation between stations or extrapolation into areas lacking wind observations. To add these features to the system in the future, it will be necessary to implement one of the more sophisticated models, requiring more specific inputs not now readily available.

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   SUBROUTINE WDCALC     ENTRY POINT 001045

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   EXTERNAL REFERENCES (BLOCK, NAME)

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    0004   COS
    0005   ATAN
    0006   SQRT
    0007   TAN
    0010   XPRR
    0011   ACOS
    0012   NADOU$
    0013   NIO2$
    0014   NIO1$
    0015   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

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    0001   000570 110L    0000   000336 1100F   0001   000074 113G    0001   000560 120L    0001   000341 151G
    0001   000471 175G    0001   000137 20L     0001   000660 226G    0001   000762 247G    0001   000770 254G
    0001   000644 90L     0000 R 000322 C1      0000 R 000323 C18     0000 R 000331 C2      0000 R 000330 C28
    0000 R 000327 C21     0000 R 000324 C27     0000 R 000317 DEG     0000 R 000325 F       0000 I 000310 I
    0000 I 000320 IDEG    0000   000471 INJP$   0000 I 000335 IPAGE   0000 I 000314 J       0000 I 000332 JDRD
    0000 I 000333 JJ      0000 I 000334 JK      0000 I 000313 KK      0000 R 000321 PI      0000 R 000144 PSI
    0000 R 000326 THICK   0000 R 000315 WD      0000 R 000311 XI      0000 R 000312 XJ      0000 R 000316 X#MND
    0000 R 000000 Z


00101          SUBROUTINE WDCALC(I,D,XWS,X,MNS,IWMND,XDRS,IDRD,N,NU,MO,     000070
00101         1MONTH,IDATE,IYEAR,UTHICK,ALAT)                               000070
00103          DIMENSION IWD(90,4),XWS(90,4),XWMNS(90),IWMND(90),XDRS(90),IDRD  000070
00103         1(90),N(90),MD(12),UTHICK(90),ALAT(90),Z(100),PSI(100)        000070
00104          DO 10 I=1,90                                                 000070
00107          XI=0.                                                        000070
00110          XJ=0.                                                        000070
00111          KK=0                                                         000071
00112          DO 20 J=1,4                                                  000074
00115          IF(IWD(I,J).GT.500.OR.XWS(I,J).GT.90.)GO TO 20               000074
00117          WD=3.141592654*(IWD(I,J))/180                                000111
00120          XI=XI-SIN(WD)*XWS(I,J)                                       000117
00121          XJ=XJ-COS(WD)*XWS(I,J)                                       000125
00122          KK=KK+1                                                      000133
00123    20    CONTINUE                                                     000141
00125          IF(KK.EQ.0)GO TO 10                                          000141
00127          XWMND=ATAN(XI/XJ)                                            000143
```

```
00130            DEG=XWMND*180/3.141592654                                              000162
00131            IDEG=DEG+.5                                                            000155
00132            IF(IDEG.LT.0)IDEG=360+IDEG                                             000165
00134            IF(XI.LT.0.AND.XJ.GE.0)IDEG=IDEG-180                                   000173
00136            IF(XI.GE.0.AND.XJ.GE.0)IDEG=IDEG+180                                   000212
00140            IWMND(I)=MOD(IDEG ,360)                                                000231
00141            XWMNS(I)=SQRT(XI**2+XJ**2)/KK                                          000235
00142      10    CONTINUE                                                               000257
00144            PI=3.141592654                                                         000257
00145            C1=TAN(.1*PI)                                                          000261
00146            C18=COS(.1*PI)                                                         000267
00147            C27=COS(27/180*PI)                                                     000273
00150            DO 90 J=1,NO                                                           000341
00153            IF(XWMNS(J).LT.0.5)GO TO 120                                           000345
00155            IF(XWMNS(J).GT.98.)GO TO 90                                            000351
00157            F=.0001458*SIN(PI*ALAT(J)/180)                                         000355
00160            THICK=JTHICK(J)                                                        000366
00161            THICK=THICK/12.                                                        000371
00162            IF(THICK.LT.0.5)THICK=0.5                                              000374
00164            C2T=.004*C18*SQRT( .000625/C18)                                        000402
00165            C2B=.9*THICK*F*(SQRT(.004*SQRT(2)*PI/(473.*F))*C27+C18)                000404
00166            C2=C2T/C2B                                                             000423
00167            IF(XWMNS(J).LT.10)PSI(1)=60-6.43*XWMNS(J)*1.68                         000426
00171            IF(XWMNS(J).GE.10)PSI(1)=35-.2*XWMNS(J)*1.68                           000437
00173            Z(1)=1/COS(PSI(1)*PI/180.)**2                                          000453
00174            DO 100 I=1,100                                                         000471
00177            Z(I+1)=SQRT(Z(I))/(XWMNS(J)*1.68)**2/C2**2+2*C1*Z(I)**.25/XWMNS(J)     000471
00177           1 /C2/1.68+C1**2+1                                                      000471
00200            PSI(I+1)=ACOS(1/SQRT(Z(I+1)))*180/PI                                   000517
00201            IF(ABS(PSI(I)-PSI(I+1)).LT.0.5)GO TO 110                               000535
00203      100   CONTINUE                                                               000544
00205            WRITE(6,1100)N(J)                                                      000544
00210      1100  FORMAT(10X,'DRIFT FOR STATION ',A5,' FAILS TO CONVERGE')               000552
00211            XDRS(J)=99.9                                                           000552
00212            IDRD(J)=999                                                            000554
00213            GO TO 90                                                               000556
00214      120   JDRD=90+IWMND(J)                                                       000560
00215            IDRD(J)=MOD(JDRD,360)                                                  000562
00216            XDRS(J)=0.                                                             000565
00217            GO TO 90                                                               000566
00220      110   JDRD=IWMND(J)+(PSI(I+1)+.5)                                            000570
00221            IDRD(J)=MOD(JDRD,360)                                                  000604
00222            XDRS(J)=XWMNS(J)*(SQRT(.004*SQRT(2)*PI/(473*F))*C27+C18)               000610
00222           1*SQRT(.000625*COS(PSI(I+1)*PI/180)/C18)                                000610
00223      90    CONTINUE                                                               000660
00225            DO 30 JJ=1,NO,20                                                       000660
00230            JK=JJ+19                                                               000707
00231            IPAGE=JK/20                                                            000712
00232            WRITE(6,1000)IPAGE                                                     000715
00235      1000  FORMAT(1H1/105X,'PAGE NO ',I1)                                         000723
00236            WRITE(6,1010)MO(MONTH),IDATE,IYEAR                                     000723
00243      1010  FORMAT(1H0////37X,'WIND SPEED (KTS) AND DIRECTION (DEG)'/              000733
00243           136X,'AND WIND DRIFT OF ICE FOR',A5,I2,', 19',I2,////10X,               000733
00243           2'STATION',7X,'002',11X,'062',11X,'122',11X,'182',11X,'MEAN',9X,        000733
00243           3'DRIFT',/12X,'NO',3X,5(5X,'SPD    DIR'))                               000733
00244            IF(JK.GT.NO)JK=NO                                                      000733
00246            DO 30 J=JJ,JK                                                          000741
```

```
00251                WRITE(6,1020)N(J),(XWS(J,I),IWD(J,I),I=1,4),XWMNS(J),    000762
00251               1IWMND(J),XDRS(J),IDRD(J)                                 000762
00265          30    CONTINUE                                                 001013
00270        1020    FORMAT(1H0,10X,A5,1X,5(4X,F4.1,3X,I3),4X,F4.2,3X,I3)     001013
00271                RETURN                                                   001013
00272                END                                                      001120
END FOR

@BRKPT PRINTS
```

APPENDIX B. THEORETICAL DEVELOPMENT OF WIND DRIFT EQUATIONS

The frictional stress between two media is assumed to be proportional to the square of the relative velocity between them. Let $\vec{V}_a$ be the wind velocity, $\vec{V}_i$ be the ice velocity, assumed to move in +x direction and $\vec{V}_w$ be the water velocity. The frictional stress ($\vec{T}_a$) between air and ice is then given by:

$$|\vec{T}_a| = k_a\rho_a|\vec{V}_a-\vec{V}_i|^2 = k_a\rho_a|\vec{V}_a|^2 \text{ since } |\vec{V}_a| >> |\vec{V}_i|$$

The stress (T_i) between ice and water is given by:

$$|\vec{T}_i| = k_w\rho_w|\vec{V}_i - \vec{V}_w|^2$$

In addition to these two forces we have the Coriolis force:

$$\vec{C} = f(\vec{V}_i x\vec{k})$$

acting on the ice where $f = 2\omega\sin\theta$. The motion is assumed to take place under the equilibrium of these three forces therefore they must vectorially add to zero.

We now choose a coordinate system whose X - axis coincides with the direction of V_i thus producing figure 3.

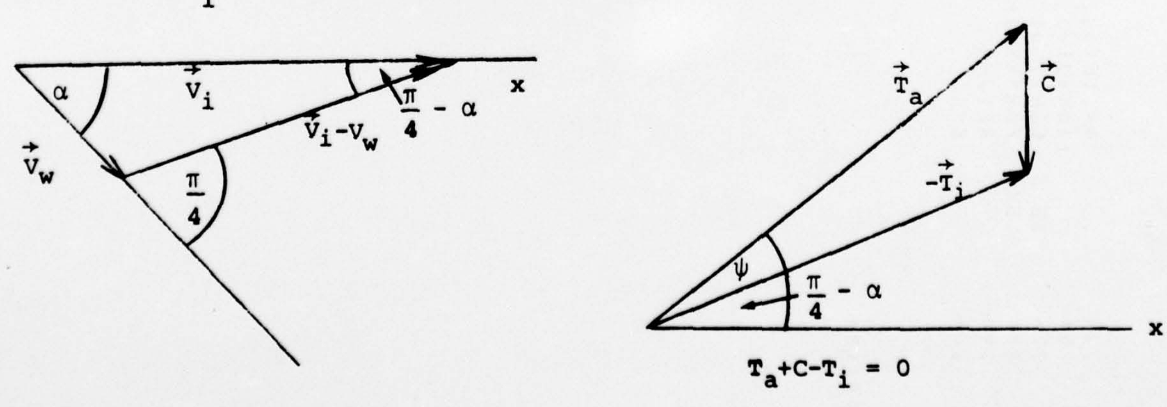

Figure 3a Velocity diagram

Figure 3b Force diagram

Referring to figure 3a we see:

$$\frac{|\vec{V}_w|}{|\vec{V}_i-\vec{V}_w|} = \frac{\sin(\pi/4-\alpha)}{\sin(\alpha)}$$

$$= \frac{\sin(\pi/4)\cos(\alpha)-\sin(\alpha)\cos(\pi/4)}{\sin(\alpha)}$$

$$= \sin(\pi/4)\cot(\alpha)-\cos(\pi/4) = \zeta$$

$$\cot(\alpha)-\cot(\pi/4) = \cos(\alpha)-1 = \frac{\zeta}{\sin(\pi/4)}$$

$$\cot(\alpha) = 1+ 2\zeta$$

again from figure 3a we have:

$$|\vec{V}_i| = |\vec{V}_w|\cos(\alpha)+|\vec{V}_i - \vec{V}_w|\cos(\pi/4-\alpha)$$

Now referring to figure 3b:

$$T_{ix} = \vec{T}_i\cdot\vec{i} = k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\cos(\pi/4-\alpha)$$

$$T_{iy} = \vec{T}_i\cdot\vec{j} = k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\sin(\pi/4-\alpha)$$

$$T_{ax} = \vec{T}_v\cdot\vec{i} = k_a\rho_a|\vec{V}_a|^2\cos\Psi$$

$$T_{ay} = \vec{T}_v\cdot\vec{j} = k_a\rho_a|V_a|^2\sin\Psi$$

$$C_x = \vec{C}\cdot\vec{i} = -mf(\vec{k}x\vec{V}_i)\cdot i = 0=-mf(\vec{V}_i x\vec{k})\cdot\vec{i}$$

$$C_y = \vec{C}\cdot\vec{J} =-mf(\vec{k}x\vec{V}_i)\cdot\vec{j} = -mf|\vec{V}_i| = f(\vec{V}_i x\vec{k})\cdot\vec{j}$$

where: m = mass per unit area

k_w = the coefficient of friction between ice and water

k_a = the coefficient of friction between air and ice

ρ_w = the density of water

ρ_a = the density of air

$\vec{i}, \vec{j}, \vec{k}$, = the unit vectors along the x, y, and z directions respectively

therefore:

$$\Sigma Y \text{ forces} = -k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\sin(\pi/4-\alpha)-mf|\vec{V}_i|+|\vec{T}_v|\sin\Psi = 0$$

$$\Sigma X \text{ forces} = -k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\cos(\pi/4-\alpha)\,|\vec{T}_v|\cos\Psi = 0$$

Solving for $\sin\Psi$ and $\cos\Psi$ and taking the ratio:

$$\tan\Psi = \frac{mf|\vec{V}_i|+k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\sin(\pi/4-\alpha)}{k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\cos(\pi/4-\alpha)}$$

$$= \tan(\pi/4-\alpha)+\frac{mf|\vec{V}_i|}{k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\cos(\pi/4-\alpha)}$$

Now since:

$$|\vec{V}_i-\vec{V}_w| = \frac{|\vec{V}_i|}{\zeta\cos(\alpha)+\cos(\pi/4-\alpha)}$$

and therefore:

$$k_w\rho_w|\vec{V}_i-\vec{V}_w|^2 = \frac{k_w\rho_w|\vec{V}_i|^2}{[\zeta\cos(\alpha)+\cos(\pi/4-\alpha)]^2}$$

we have:

$$\tan\Psi = \tan(\pi/4-\alpha)+\frac{B}{|\vec{V}_i|}$$

where:

$$B = \frac{mf[\zeta\cos\alpha+\cos(\pi/4-\alpha)]^2}{k_w\rho_w\cos(\pi/4-\alpha)}$$

Now since:

$$T_{vx} = |\vec{T}_v|\cos\Psi = T_{ix} = k_w\rho_w|\vec{V}_i-\vec{V}_w|^2\cos(\pi/4-\alpha)$$

$$= \frac{k_w \rho_w |V_i|^2 \cos(\pi/4-\alpha)}{[\zeta\cos(\alpha)+\cos(\pi/4-\alpha)]^2}$$

we get:

$$|\vec{T}_v| = \frac{k_w \rho_w |\vec{V}_i|^2 \cos(\pi/4-\alpha)}{[\zeta\cos(\alpha)+\cos(\pi/4-\alpha)]^2 \cos\Psi}$$

Now since:

$$|\vec{T}_v| = k_a \rho_a |\vec{V}_a|^2$$

we get:

$$k_a \rho_a |\vec{V}_a| = \frac{k_w \rho_w |\vec{V}_i|^2 \cos(\pi/4-\alpha)}{[\zeta\cos(\alpha)+\cos(\pi/4-\alpha)]^2 \cos\Psi}$$

or:

$$\frac{|\vec{V}_i|}{|\vec{V}_a|} = [\zeta\cos(\alpha)+\cos(\pi/4-\alpha)] \sqrt{\frac{k_a \rho_a \cos(\Psi)}{k_w \rho_w \cos(\pi/4-\alpha)}}$$

Now from above we have:

$$\frac{B}{|\vec{V}_i|} = \tan(\Psi)-\tan(\pi/4-\alpha)$$

and multiplying this by the previous equation we get:

$$\frac{B}{|\vec{V}_a|} = [\zeta\cos(\alpha)+\cos(\pi/4-\alpha)] \sqrt{\frac{k_a \rho_a \cos\Psi}{k_w \rho_w \cos(\pi/4-\alpha)}} \; [\tan(\Psi)-\tan(\pi/4-\alpha)]$$

The equation for ζ is derived from Ekman theory, as follows:

$$V_w = \frac{k_w \gamma^2}{\sqrt{f}} \sqrt{\frac{\rho_w}{\mu}}$$

where: $\gamma = |\vec{V}_i - \vec{V}_w|$

μ = the coefficient of viscosity between ice and water

$$\sqrt{\frac{\rho_w}{\mu}} = \frac{\pi}{N|\vec{V}_w|\sqrt{f}}$$

Where: $N = D/|\vec{V}_i|$ and is the depth of frictional mixing. This has been evaluated as N = 473, (Shuleikin). Now since:

$$\zeta = \frac{|\vec{V}_i|}{\gamma}$$

we derive:

$$\zeta = \sqrt{\frac{\pi k_w \sqrt{2}}{Nf}}$$

$$= \sqrt{\frac{\pi k_w \sqrt{2}}{473f}}$$

It can be assumed with sufficient accuracy that the density of air (ρ_a) is 1.25×10^{-3} gm per cm^3, the density of water is 1 gm per cm^3, the coefficient of friction between ice and water (k_w) is 4×10^{-3} and between air and ice (k_a) is 2×10^{-3}. From observations it has been determined that $\alpha = 27°$. In addition, since the density of ice is .9 and the mass per unit area of ice (m) is the density times the thickness (L), m = .9L. Therefore: from the equation for $\frac{B}{|\vec{V}_a|}$ above, we get:

$$\frac{1}{|\vec{V}_a|} = \frac{\rho_w k_w \cos(18°)}{.9Lf[\zeta\cos(27°)+\cos(18°)]} \sqrt{\frac{6.25\times10^{-4}\cos(\Psi)}{\cos(18°)}} \left[\sqrt{\sec^2(\Psi)-1} - \tan(18°)\right]$$

let: $Z = \dfrac{1}{\cos^2(\Psi)}$

then $$\frac{1}{|\vec{V}_a|} = \frac{.004\cos(18^\circ)\frac{1}{Z^{1/4}}\sqrt{\frac{6.25\text{x}10^{4}}{\cos 18^\circ}}\left[\sqrt{Z-1} - \tan 18^\circ\right]}{.9Lf\left[\frac{.004 \quad 2\pi}{473f} \quad \cos(27^\circ)+\cos(18^\circ)\right]}$$

$$\tan(18^\circ) = \frac{Z^{1/4}.9Lf\left[\frac{.004 \quad 2\pi}{473f} \quad \cos 27^\circ+\cos 18^\circ\right]}{|\vec{V}_a|\left[.004\cos 18^\circ \sqrt{\frac{6.25\text{x}10^{-4}}{\cos 18^\circ}}\right]} = \sqrt{Z-1}$$

let: $C_1 = \tan(18^\circ)$

$$C_2 = \frac{.004\cos(18^\circ)\sqrt{\frac{6.25\text{x}10^{-4}}{\cos(18^\circ)}}}{.9Lf\left[\frac{.004 \quad 2\pi}{473f} \quad \cos(27^\circ)+\cos(18^\circ)\right]}$$

then: $$\sqrt{Z-1} = C_1 + \frac{Z^{1/4}}{C_2|\vec{V}_a|}$$

$$Z = C_1{}^2 + \frac{Z^{1/2}}{C_2{}^2|\vec{V}_a|^2} + \frac{2C_1Z^{1/4}}{C_2|\vec{V}_a|} + 1$$

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NOO-RP- 8-S

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): WIND DRIFT OF SEA ICE: A SUPPLEMENT TO THE NAVAL OCEANOGRAPHIC OFFICE NUMERICAL ICE FORECASTING SYSTEM.

5. TYPE OF REPORT & PERIOD COVERED: Reference Publication

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): Donald J. Gerson, Lloyd S. Simpson

8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Naval Oceanographic Office (NAVOCEANO)
Washington, DC 20373

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:

11. CONTROLLING OFFICE NAME AND ADDRESS:
Naval Oceanographic Office (NAVOCEANO)
Washington, DC 20373

12. REPORT DATE: September 1976

13. NUMBER OF PAGES: 21 12 28p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report):
Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

250 450

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Ice Forecasting
Numerical Ice Forecasting
Wind Velocity
Wind Velocity Averaging
Ice Drift Computation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The numerical ice prediction system described in RP 8 has been in use since 1971. Its outputs, however, have been related only to ice growth, not ice drift. An addition to the system now provides an output of daily ice drift at 62 arctic stations. Drift is calculated as a function of wind stress, water stress, and Coriolis force. The computer output is sufficiently accurate for ice drift in the locality of the station whose wind observations were input to the model. However, more recent research indicates that for

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. greater accuracy and for computations of divergence and convergence interaction between floes must be considered.

AD-A038 019 NAVAL OCEANOGRAPHIC OFFICE WASHINGTON D C F/G 8/12
WIND DRIFT OF SEA ICE: A SUPPLEMENT TO THE NAVAL OCEANOGRAPHIC --ETC(U)
SEP 76 D J GERSON, L S SIMPSON
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2 OF 2
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p. 16	figure 3a	change	$\vec{V}_i - V_w$	to	$\vec{V}_i - \vec{V}_w$
p. 17	line 5	"	$\cos(\alpha)-1$	to	$\cot(\alpha)-1$
"	" 6	"	$1+2\zeta$	to	$1+\sqrt{2}\zeta$
"	" 12	"	$\vec{T}_v$	to	$\vec{T}_a$
"	" 13	"	$\vec{T}_v$	to	$\vec{T}_a$
p. 18	" 2	"	$\lvert\vec{T}_v\rvert$	to	$\lvert\vec{T}_a\rvert$
"	" 3	"	$\cos(\pi/4-\alpha)\lvert\vec{T}_v\rvert$	to	$\cos(\pi/4-\alpha)+\lvert\vec{T}_a\rvert$
"	" 16	"	T_{vx}	to	T_{ax}
"	" "	"	$\lvert\vec{T}_v\rvert$	to	$\lvert\vec{T}_a\rvert$
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"	" 5	"	$\lvert\vec{T}_v\rvert$	to	$\lvert\vec{T}_a\rvert$
p. 21	" 2	"	$\sqrt{\frac{6.25X10^{4}}{\cos 18^\circ}}$	to	$\sqrt{\frac{6.25X10^{-4}}{\cos 18^\circ}}$
"	" 3	"	$\tan(18^\circ)=$	to	$\tan(18^\circ)+$
"	" "	"	$\sqrt{\frac{6.25+10^{=4}}{\cos 18^\circ}}$	to	$\sqrt{\frac{6.25+10^{-4}}{\cos 18^\circ}}$